Proceedings of the 2003 IEEE
International Conference on Robotics,Intelligent Systems and Signal Processing
Changsha, China - October 2003

Adaptive RAKE-Blind Source Recovery Algorithms for 3GPP UMTS/WCDMA Downlink Receivers

Khurram Waheed, Keyur Desai, Fathi M. Salem

Circuits, Systems and Neural Networks Laboratory
Michigan State University
East Lansing, MI 48824-1226
Email: {waheedkh, desaikey)@msu.edu, salem@egr.msu.edu

Abstract

Wideband Code Division Multiple Access (WCDMA) is the dominant air interface for the Universal Mobile Telephone Service (UMTS) Frequency Domain Duplex (FDD) mode and for future IMTS wireless networks. The transmitted CDMA signals from Base Station(BS) propagate through noisy multipath fading communication channels before arriving at the receiver of the mobile station (MS). In contrast to classical single-user detection (SUD) algorithms, which do not provide the requisite performance for modern high data rate applications, optimal multi-user detection (MUD) approaches require a lot of a-priori information not available to the User Equipment (UE). We propose two adaptive approaches, namely RAKE-Blind Source Recovery (RAKE-BSR) and RAKE-Principal Component Analysis (RAKE-PCA) that fuse an info-theoretic stage into a standard RAKE receiver. This results in robust detection algorithms with performance exceeding the standard LMMSE detectors for WCDMA systems under conditions of congestion, imprecise channel estimation and unmodeled multiple access interference (MAI).

1. Introduction

Wideband CDMA (WCDMA) will be a dominant technology for third generation (3G) and future wireless communication systems and forms an integral part of the CDMA2000, 3rd Generation Partnership Project (3GPP) International Mobile Telecommunication Standard (IMTS-2000) [1-3]. In a CDMA system, the symbol train to a user may be detected using either a single-user or a multi-user detector. A single-user detector (SUD) such as Matched Filter (MF) detector, Zero Forcing (ZF) detector, RAKE [5, 10, 12] etc., does not model the multiple access interference (MAI) due to the presence of other users and extraneous signals in its signal path, rather it treats all interfering users and disturbances as additive noise. This severely limits its detection performance and SUD fails to provide the performance levels vital to modern high data rate applications [12].

In contrast, a multi-user detector (MUD) includes all the users in the signal model. Significant improvement can be obtained with a multi-user receiver [5, 6, 9, 14, 15]. However the optimal MUD [12] is computationally intensive and requires several dynamic system parameters to be known precisely. Several other linear multi-user detection (MUD) techniques such as Best linear unbiased estimator (BLUE), linear minimum mean squared error (LMMSE) estimator [4, 8, 9, 15] have been proposed for the wireless downlink based on the linear convolutive channel model. In practical situations most of these estimators require extensive knowledge of channel parameters and massive computational power. One approach is to use sub-optimal block-level implementations, where performance degrades quickly if the a-priori channel estimates are far from true system parameters. Adaptive approximations of these algorithms also require some a-priori information for correct initialization and may not match the performance of the algebraic counterparts under all conditions.

For the proposed 3GPP UMTS FDD [1, 3] and future tightly synchronous CDMA standards, the user specific spreading is done by Orthogonal Variable Spreading Factor (OVSF) codes, while the cell specific complex scrambling is done using a set of long gold sequences (and/or Kasami sequences) [3]. Long codes have their own advantages such as code-hopping which results in similar performance for all users in the system (i.e., better QoS). In addition long codes also result in improved power control for users with relatively smaller data rates in the system and better rejection of extra-cellular interference (i.e., lower effective BER) [6]. Contrarily, the use of long scrambling codes makes the implementation of the exact linear detection algorithms impractical due to the excessive computational requirements [8, 15].

In this paper we propose two adaptive approaches, suitable for the WCDMA downlink with long scrambling code, namely RAKE-Blind Source Recovery (RAKE-BSR) and RAKE-Principal Component Analysis (RAKE-PCA) that fuse an info-theoretic stage into a standard RAKE receiver. This results in robust detection algorithms with performance exceeding the standard LMMSE detectors for WCDMA systems under

conditions of congestion, imprecise channel estimation and unmodeled MAI.

2. UMTS FDD Forward Link (or Downlink)

Consider the forward linkfor a modern wireless 3G UMTS FDD (best known as WCDMA) cellular mobile communications network [1-3]. User specific data is delivered to the physical layer in blocks often termed as Transport Blocks (TB) [2], which include bits for CRC, FEC etc. The transport channel multiplexer (or a parallel-to-serial converter *P/S*) converts all the data to a single *BPSK* stream. After interleaving and addition of physical channel information for power control (*TPC*), pilot, TFCI etc., the data stream comprises of two dedicated logical channels, one for data (*DPDCH*) and one for corresponding control (*DPCCH*) information, in multiplexed form they form one user specific dedicated physical data channel (*DPCH*) [3]. However, note that in case several data streams are associated to a single user, they can share the same logical control channel. Before transmission, the data goes through a serial-to-parallel (*S/P*) converter for QPSK modulation.

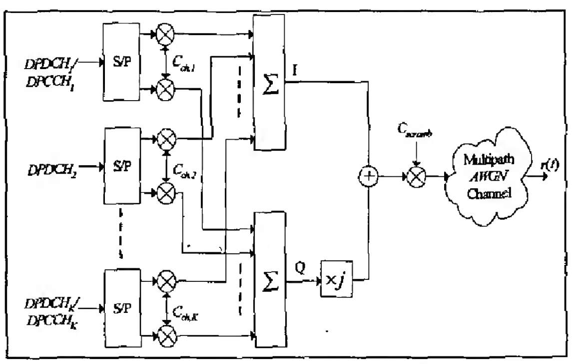


Figure 1: Signal generation based on the proposed 3GPP UMTS FDD standard

Each user specific stream is first spread using a relatively short (4-512 chips) OVSF channelization code C_{ch} (or real user-specific spreading code, $s_k(t)$). The parallel channels are then mapped to the I and the Q branches. At this stage the data streams for all the users in a cell are summed together. This combined QPSK stream is subsequently scrambled by a long (38400 chips) scrambling code C_{scramb} (or cell-level complex gold code, $c(t)$). The collective data for all users is then modulated and synchronously transmitted via the transmission medium, which we assume to be a wide sense stationary slowly fading multipath frequency selective channel [1 - 3].

All physical channels transmitted from a BS are mutually orthogonal at the time of transmission as the spreading codes are the OVSF (or Walsh Hadamard codes), which are confined to the symbol period only. Different users can have different data-rates, which is accommodated by assigning different length OVSF spreading sequences $s_k(t)$ in a global prefix-free code assignment tree [3]. The downlink system is designed to be tightly synchronous at the frame level [1]. The intra-cell multiple user signals sharing the same multipath environment are considered to be the main cause of the Multiple Access Interference (MAI) in the received signal for a desired user [5, 12].

2.1 WCDMA Downlink Signal Model

The received signal at the mobile receiver within a transmitted frame of length T_F can be represented by

$$r(t)=\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{l=0}^{L-1}\sqrt{\varepsilon_{kn}(t)}b_k(n)h_l(t)s_k(t-nT-\tau_l)+n(t) \quad (1)$$

Where ε_{kn} is the energy of the n^{th} symbol for the k^{th} user, $b_k(n)\in\{\pm1\pm i\}$ is the n^{th} symbol for the k^{th} user, h_l and τ_l are the l^{th} path's gain co-efficients and delay, respectively. $n(t)$ is the additive noise and $s_k(t)$ is the k^{th} user's signature code (or spreading sequence) generated by

$$s_k(t)=\sum_{m=0}^{G-1}\alpha_k(m)p(t-mT_c) \quad (2)$$

$\alpha_k(m)\in\{-1,1\}$; $0\le m\le G-1$ is a real OVSF spreading sequence for the k^{th} user containing G chips per symbol, i.e., $G=T_b/T_c$. $p(t)$ is a chipping pulse of duration T_c. T_b being the symbol period. $c(t)\in\{\pm1\pm i\}$ is the complex cell-specific gold scrambling sequence [3].

Under the assumption of time-invariance, the model in (1) can be compactly written in a vector-matrix format as

$$\bar{r}=HCS\bar{b}+\bar{n} \quad (3)$$

Where, H is a $(NG+L-1)\times NG$ multipath propagation co-efficient matrix containing the channel coefficients. S is a $NG\times NG$ block diagonal matrix with the matrix of spreading codes forming the diagonal elements, $\bar{b}$ is an NG-d vector containing the user symbols, while $\bar{n}$ is the ($NG+L-1$)-d channel noise vector with covariance matrix Q. C is the $NG\times NG$ complex diagonal scrambling matrix. N being the number of symbols within a frame time T_F. The structure of the above defined matrices and vectors is given by

$$H=\begin{bmatrix} h_0 & 0 & \cdots & 0 \\ \vdots & \ddots & & \vdots \\ h_{L-1} & & \ddots & 0 \\ 0 & \ddots & & h_0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & h_{L-1} \end{bmatrix}$$

$$S' = diag\left[\bar{S} \quad \bar{S} \quad \cdots \quad \bar{S}\right],\ \bar{S} = \left[s_1 \quad s_2 \quad \cdots \quad s_k\right]$$

$$\bar{b} = \left[b(1)^T \quad b(2)^T \quad \cdots \quad b(N)^T\right]^T,$$

$$b(n) = \left[\sqrt{\varepsilon_{1n}}b_1(n) \quad \sqrt{\varepsilon_{2n}}b_2(n) \quad \cdots \quad \sqrt{\varepsilon_{kn}}b_K(n)\right]^T$$

$$C = diag[c_1 \quad c_2 \quad \cdots \quad c_{NG}];\ c_i \in \{\pm 1 \pm i\};\ 1 \le i \le NG$$

The compact linear model (3) is useful in deriving the linear detectors such as matched filter (MF), linear minimum mean squared error (LMMSE) etc. (see, section 3) for recovery of the transmitted symbol train for a desired user equipment (UE). However, the size of the above model is excessively large due to the dimension of the long scrambling code. A number of approaches will be discussed in the subsequent section to recover the desired user's symbol train at UE/MS while keeping in mind the constraints of performance and ease of implementation.

2.2 Channel Estimation Using The Common Pilot Channel (CPICH)

Good Channel Estimation is vital to the performance of most conventional detection schemes. WCDMA includes provision of Common Pilot Channels (*CPICH*), which may be implemented for active channel estimation. *CPICH* is a fixed rate (30 kbps, G=256) downlink physical channel that carries a pre-defined bit sequence [1]. If applicable, *CPICH* allows the UE/MS to equalize the channel in order to achieve a phase reference with the *SCH* (Synchronization Channel). The standard defines a fixed channelization code for the Primary *CPICH*.

2.2.1 Channel Estimation Procedure

In order to outline a simple and practical channel estimation technique using *CPICH* [5], we assume that the transmitted pilot comprises of a stream of a single symbol train of $1-i$, and uses an all ones spreading code (i.e., the first OVSF code)

1. For each independent multipath, multiply the incoming symbol train with the corresponding delayed scrambling sequence.
2. Remove the modulation form CPICH by simply multiplying the CPICH data by its conjugate, i.e., $1+i$. The resulting channel estimate is noisy because of AWGN and multiple-access interference.
3. Pass the noisy channel estimate through a smoothing filter to achieve better noise immunity. This filter can be either a moving average window of length $2M+1$, e.g.,

   $$\hat{h}_i = \frac{1}{2M+1}\sum_{k=-M}^{M} p_{ik} \qquad (4)$$

   Since, a moving UE/MS represents a dynamic channel, the channel estimates may be processed using a relatively smaller factor M followed by a single-zero smoothing filter

   $$\bar{h}_i = (1-\rho)\bar{h}_i + \rho\hat{h}_i;\ \text{where } 0 \le \rho \le 1 \qquad (5)$$
4. Decimate or interpolate the filtered channel estimate obtained in step 2 to match the data rate of the CPICH to the data rate of the DPCCH/DPDCH.

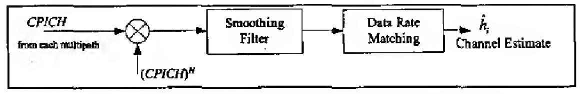


Fig. 2. Channel Estimation Using CPICH

This simple technique works well in most cases because the channel is assumed to be stable for the symbol duration.

3. WCDMA Detection Structures

In this section, we first briefly describe the linear detection schemes such as the matched filter (MF), multipath version of matched filter or RAKE receiver and the linear minimum mean squared error (LMMSE) detector [5, 12, 15]. Other linear detector formulations such as the least squares (LS) or the zero forcing (ZF) detector, best linear unbiased estimator (BLUE) detector are not discussed as their performance is worse as compared to the LMMSE detector, see [8, 10, 12, 15] for more details.

3.1.1 Matched Filter (MF) Detector

The standard matched filter is a single user detector, which just utilizes the user's, own signature sequence to make the best possible estimate of user's transmitted sequence from the raw chip data received at the UE/MS. The detection algorithm completely ignores the presence of convolutions due to multipaths in the in the receiver environment as well as the MAI due to additional users sharing the resources. In case of WCDMA system, the user's symbol undergoes spreading as well as scrambling, therefore the MF detector becomes

$$\hat{b}_{i,MF}(n) = s_i^H C^H(n)\bar{r}((n-1)G+1:nG) \qquad (6)$$

where $C^H(n) = \left\{diag\left[c_{(n-1)G+1} \quad \cdots \quad c_{nG}\right]\right\}^H$

3.2 RAKE Detector

The RAKE detector in CDMA is created using multiple chip-delayed MF detector fingers in parallel. The RAKE receiver first identifies three or more (depending on the number of implemented fingers) strongest multipath signals arriving at the receiving antenna using a maximal ratio path search algorithm [5, 12]. These multipath signals are combined after adjustment for their corresponding delays (and possibly phase and path attenuation if channel estimation is available) to produce a relatively stronger received signal chip stream. In this

work, we assume that the RAKE receiver to be implemented with the knowledge of both channel multipath delays (maximal ratio path search) as well as the corresponding multipath attenuation co-efficients (channel estimation). The RAKE detector for WCDMA system is given by

$$\hat{\bar{b}}_{i,RAKE}(n) = s_i^H C^H(n)\hat{H}^H(n)\bar{r}((n-1)G+1:nG) \qquad (7)$$

where, $C^H(n)$ is as defined above , and $\hat{H}^H(n)$ is the hermitian of the estimated channel estimate filter.

3.3 Linear Minimum Mean Squared Error (LMMSE) Detector.

The optimal LMMSE detector is considered to be the best linear detector for DS-CDMA reception. While other linear detectors such as LS, ZF, BLUE etc. do not provide good performance in the presence of excessive noise (especially colored noise). LMMSE detectors do a trade-off by not performing perfect orthogonalization of received signal stream at low SNRs by trying to minimize additive noise variance. The LMMSE detector for the WCDMA system is given by

$$\hat{\bar{b}}_{i,LMMSE} = S_i^H C^H \hat{H}^H(\sigma^2 \hat{H}\hat{H}^H + \hat{Q})^{-1}\bar{r} \qquad (8)$$

where

$S_i = diag\left[\bar{S}_i \quad \bar{S}_i \quad \cdots \quad \bar{S}_i\right], \bar{S}_i = [0 \quad \cdots \quad s_i \quad \cdots \quad 0]$, s_i being the i^{th} user's signature code and $R = \mathrm{E}\left[\bar{r}\,\bar{r}^H\right] = (\sigma^2 HH^H + Q)$ is the auto-correlation matrix for the signal chip train received at the UE/MS, σ^2 being the average power of transmitted user signals.

Note that the dimension of H is impractical for the implementation purpose. Typically LMMSE is implemented on mG-sized blocks of received data and is called block LMMSE (B-LMMSE). LMMSE detector can typically be implemented by adding a pre-processing stage before RAKE receiver. The data correlation matrix may be adaptively estimated resulting in adaptive LMMSE implementations [4, 6, 15].

3.4 RAKE-Blind Source Recovery (RAKE-BSR) and RAKE-Principal Component Analysis (RAKE-PCA) Detectors

RAKE-BSR and RAKE-PCA are two new proposed adaptive detectors [14], which utilize the same knowledge as a RAKE receiver. An info-theoretic adaptive weighting matrix of dimension $G\times G$ is introduced into the RAKE structure, which gives a big performance boost to the standard RAKE receiver. The performance of RAKE-BSR/RAKE-PCA exceeds the performance of LMMSE detectors under the conditions of high network congestion, imprecise channel estimation, and unmodeled inter-cellular interference etc [14]. The closed form structure of these proposed detectors is given by

$$\hat{\bar{b}}_{i,RAKE-ICA/PCA} = S_i^H C^H \tilde{W}\hat{H}^H\bar{r} \qquad (9)$$

where $\tilde{W} = diag\left[A \quad A \quad \cdots \quad A\right]$, and A is the $G\times G$ matrix that is adaptively estimated either using static BSR (ICA) or PCA algorithms.

We propose to adapt the matrix A using the natural gradient update laws [11, and the references therein]. However, there exist several other methods for ICA/PCA and any other suitable method may be used for these adaptations [7, and the references therein]. This blind adaptation of the A matrix has several advantages and improves the performance of the overall equalization process in several ways. Firstly, it can counter artifacts in the estimated channel co-efficients $\hat{H}$. Secondly, the channel estimation process (as in RAKE receivers) may be limited by the structure (such as number of fingers) and may estimate only a few of the dominant channel parameters. $\tilde{W}$ stage in (9) tends to counteract this anomaly, as best as possible, and provides better performance than LMMSE in such cases [14]. Thirdly, this adaptive stage minimizes the effect of the additive channel noise, which may have an unmodeled intricate underlying structure. Lastly, the natural gradient ICA /PCA algorithms inherently reduce near-far problems by removing any ill conditioning in the signal space for all the users in the system. This results in all the mobile users in the system to have a BER performance similar to the average BER performance of the downlink channel [6, 14]. The matrix A is adaptively estimated using the update laws

$$A(k+1) = A(k) + \eta_k \Delta A(k) \qquad (10)$$

where

$$\Delta A(k) = \begin{cases} (I - \varphi(y(k))y(k)^H)A(k) & \text{for static BSR/ICA} \\ (I - y(k)y(k)^H)A(k) & \text{for PCA} \end{cases}$$

and $\varphi(.)$ is a nonlinear score function [12, 13] which depends on the underlying distribution structure of the signals involved. For QPSK signal, a suitable score-function [13] is

$$\varphi_i(y_i) = \upsilon_i y_i - \alpha_i\left(\tanh\left(\beta_i \operatorname{Re}\{y_i\}\right) + \tanh\left(\beta_i \operatorname{Im}\{y_i\}\right)\right) \qquad (11)$$

Of these proposed RAKE-BSR/RAKE-PCA structures, RAKE-BSR exhibits relatively faster and more stable convergence [12, 14]. However, in CDMA systems the underlying code structure is "orthogonal", and RAKE-PCA may converge to a slightly lower BER solution if the channel impairments are linear in nature. Note that in (RAKE-ICA), if the channel estimate $\hat{H}$ [5] is either not available or changes very dynamically, the detector can be estimated without using the channel estimate and the structure reduces to Matched Filter BSR/PCA, i.e.,

$$\hat{\bar{b}}_{i,MF-BSR/PCA} = S_i^H C^H \tilde{W}\bar{r} \qquad (12)$$

The performance of this structure is better than MF alone, and approaches RAKE performance as the underlying matrix A converges. However, in this paper due to space limitation we will not discuss this structure any further.

4. Simulation Results

The proposed algorithms can be easily applied to multirate WCDMA transmission. However, for a clear comparison of the proposed algorithms with the conventional approaches, we restrict ourselves to the case where all the users have the same data rate. All the user-specific codes are OVSF with a spreading gain G of 64. The long scrambling code is the complex gold code and has the frame-length of 38400 chips (10ms). The channel is assumed to be a wide sense stationary slowly fading with several possible multiple paths to the UE/MS. The transmitted signal is also corrupted by additive white Gaussian noise (AWGN) during the transmission. The simulated SNR range for all simulations is from -10 to 20 dB. The dominant multi-path delays and attenuation co-efficients for the signal received at the UE/MS are assumed fixed (i.e., the UE/MS is assumed to be static). Further all the multi-path attenuation co-efficients are assumed to be complex, i.e., each multipath applies both scaling and rotation to the propagated signal.

For all the included simulations, the received WCDMA signal comprises of five multipaths with delays of 0, 1, 2, 3 and 4 chips. The corresponding channel attenuation co-efficients are chosen to be,

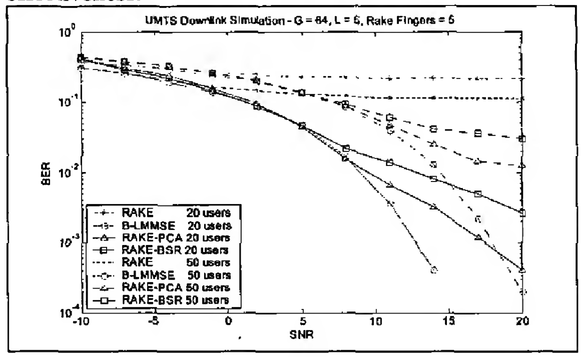
$$h=\left[0.31\angle 36^\circ \quad 0.26\angle 34^\circ \quad 0.21\angle 31^\circ \quad 0.18\angle 37^\circ \quad 0.13\angle 34^\circ\right]$$

The multipath channel is estimated online. The UE/MS and BS are assumed to be in perfect synchronism. A decaying time-adaptive learning rate is chosen for all the adaptive algorithms. The B-LMMSE algorithm is applied on a block size of G chips; the auto-correlation matrix (for the B-LMMSE algorithm) is computed from the whole ensemble of the received data. The conjugate of the channel filter H, is applied recursively. These steps were done to ensure that the performance of the simulated B-LMMSE is not restricted due to implementation. We provide results for two congestion scenarios of 20 users (approx. 30% congestion) and 50 users (approx 80% congestion). The final symbol decision stage for all algorithms is given by

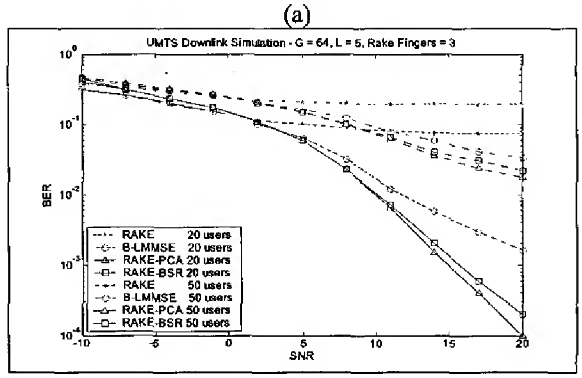
$$\psi(y_n)=sign\left(\mathrm{Re}\{y_n\}\right)+sign\left(\mathrm{Im}\{y_n\}\right)i \qquad (13)$$

In the first comparison (Fig. 3a), the channel estimation is done for all the multipaths in the signal generation model. It is observed that the performance of the proposed algorithms RAKE-PCA and RAKE-BSR is very similar to B-LMMSE for lower SNR values. Under good SNR conditions, the performance of the B-LMMSE algorithm is better than the proposed algorithms.

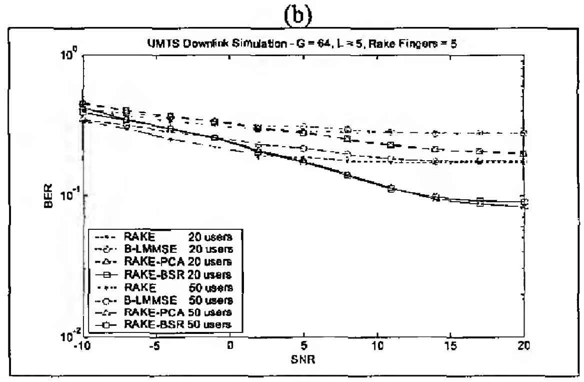
However, note that for the B-LMMSE the auto-correlation matrix is estimated using 5000 symbols, while only 1000 instantaneous adaptations (for $K = 50$) are done for the proposed algorithms. In case more adaptations are done, the performance of proposed algorithms will approach the LMMSE limit, but even the performance attained with a limited number of iterations exhibits their effectiveness.



(a)



(b)



(c)

Figure 3. WCDMA Downlink System for K=20, 50 users, Performance Comparison with: (a) Perfect Channel Estimation, (b) Imperfect Channel Estimate, (c) Imperfect Channel with Inter-Cellular Interference

In the second comparison (Fig. 3b), the channel estimate is restricted to the three dominant paths only, which

correspond to the choice of delays 0, 1 and 2 in this case. In this case it is observed that the detection performance of the proposed RAKE-BSR and RAKE-PCA algorithms exceeds B-LMMSE at all SNRs. Comparing both RAKE-PCA and RAKE-BSR, it is observed that the performance of RAKE-PCA is approximately 1% better than RAKE-BSR. But RAKE-BSR has other advantages (as discussed in section 3.4) of stability and smaller energy of the computed filtering matrix $\tilde{W}$. Another important observation in this case is that at very low SNRs, RAKE gives the best performance, but as the SNR improves the proposed algorithms can achieve very small BER. Therefore, an SNR based switching mechanism can be developed to switch between the standard RAKE and the proposed algorithms, which just constitute an additional adaptive stage in the structure of the RAKE receiver.

In the third scenario (Fig. 3c), both the channel estimate is assumed to imprecise as in the previous comparison with only three dominant multipaths out of five estimated. In addition, the received signal is corrupted by extra-cellular signals of the neighboring cell BS. This is a realistic scenario in busy metropolitan areas, where there exist several dominant multipaths and the cell size is also kept relatively small to maximize the number of users per unit area. Inter-cellular interference is also critical when the UE/MS is on the cell boundary and undergoes a soft (or soft-softer) hand-over. The intercellular interference is unmodeled MAI and severely limits the performance of the detection algorithms. For the purpose of simulation this auxiliary BS interference is assumed to have half the energy of the primary BS. It is observed that the proposed RAKE-BSR/RAKE-PCA algorithms exhibit better immunity to this excessive unmodeled MAI and retain their qualitative performance advantage over the conventional algorithms.

5. Conclusions

We have proposed two info-theoretic extensions of the standard RAKE detector namely RAKE-Blind Source Recovery (RAKE-BSR) and RAKE-Principal Component Analysis (RAKE-PCA). These detection schemes add an adaptive info-theoretic stage, based on higher-order statistics for RAKE-BSR and second-order statistics for RAKE-PCA, to the standard RAKE detector. This makes the resultant hybrid detector more robust to imperfections in channel estimates; unmodeled MAI and other slowly varying channel effects etc. Of these proposed algorithms, RAKE-BSR is more immune to synchronization errors between UE/MS and BS, possesses faster convergence and is better capable to cater for various dynamic and time-varying channel effects as compared to RAKE-PCA. However, for the presented WCDMA results RAKE-PCA demonstrates a slight performance advantage. This is due to the fact that the simulated channel imperfections are only linear, the channel synchronization is perfect and the underlying code structure is orthogonal.

6. References

[1] 3rd Generation Partnership Project (3GPP), "UE Radio Transmission and Reception (FDD)," TR 25.101, V4.5.0, June 2002.

[2] 3rd Generation Partnership Project (3GPP), "Physical channels and mapping of transport channels onto physical channels (FDD)," TS 25.211, V3.3.0, June 2002.

[3] 3rd Generation Partnership Project (3GPP), "Spreading and Modulation (FDD)," TS 25.213, V4.5.0, June 2002.

[4] D. Gesbert, J. Sorelius, P. Stoica, A. Paulraj, "Blind multi-user MMSE detectior for CDMA signals in ISI channels", in *IEEE Communications Letters*, Vol. 3, No. 8, pp. 233-235, August 1999.

[5] H. Holma and A, Toskala, *WCDMA for UMTS Radio Access for Third Generation Mobile Communications*, John Wiley & Sons, Inc., ISBN: 0471486876, 2001.

[6] M. Honig, U. Madhow and S. Verdú, "Blind Adaptive Multiuser Detection," in *IEEE Trans. on Information Theory*, vol. 41, no. 4, pp. 944-960, July 1995.

[7] J. Joutsensalo, T. Ristaniemi, "Blind multi-user detection by fast fixed point algorithm without prior knowledge of symbol level timing," in *Proc. of the IEEE Signal Processing Workshop on Higher Order Statistics*, Ceasarea, Israel, pp. 305-308, June 14-16 1999.

[8] H. H. Mahram, H. E. Boll, and G. Alirezaei, "Performance Evaluation of Advanced Receivers for WCDMA Downlink Detection," in *Proc. of 5th Int'l Symp. on Wireless Personal Multimedia Communications* WPMC-2002, Honolulu, Hawaii, USA, October 2002, to appear.

[9] O. Prator, C. Unger, A. Zoch and G. P. Fettweis, "Performance of Adaptive Chip Equalization for the WCDMA Downlink in Fast Changing Environments," in *IEEE 7th Int'l Symposium on Spread Spectrum Technology and Applications ISSSTA-02*, Prague, Czech Republic, Sept 2002, vol. 1, pp. 273-277.

[10] J. G. Proakis, *Digital Communications*, Fourth edition, McGraw-Hill, 2001.

[11] F. M. Salam; G. Erten, and K. Waheed, "Blind Source Recovery: Algorithms for Static and Dynamic Environments," in *Proc. of the INNS-IEEE Int'l Joint Conference on Neural Networks*, IJCNN-2001, Vol. 2, pp. 902-907, July 14-19, 2001.

[12] S. Verdu, *Multiuser Detection*, Cambridge University Press, 1998.

[13] K. Waheed, F. M. Salam: "New Hyperbolic Source Density Models For Blind Source Recovery Score Functions," in *2003 Int'l Symp. on Circuits & Systems*, ISCAS-2003, May, 2003 Bangkok, Thailand; in press

[14] K. Waheed, K. Desai, F. M. Salem: "Adaptive and Blind Info-Theoretic Multi-User Detection Algorithms for DS-CDMA and WCDMA Downlink Systems," submitted March 2003 to *IEEE Trans. on Neural Networks, Special Issue on Information Theoretic Learning*, TNN-ITL 2003

[15] S. Werner and J. Lilleberg, "Downlink Channel Decorrelation in CDMA Systems with long Codes" in *IEEE Vehicular Technology Conference*, VTC'99 Spring, Houston, Texas, USA, Vol. 2, pp. 1614–1617, May 1999.